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# STEAM GENERATOR CORROSION DURING CHEMICAL CLEANING

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## ABSTRACT

Loop experiments were performed to evaluate steam generator corrosion during a Bruce "A" steam generator tubesheet chemical clean. I-600 was unattacked. Welds were attacked at two to four times the base metal rate. The weld fusion line was attacked at about five times the base metal rate. Welds close to I-600 such as the shroud seam, tubesheet to thickshell, blowdown block to shell, shroud foot, and blowdown header to shroud welds, with the exception of the thick shell to main shell weld, were the most severely attacked. Maximum corrosion resulting from a single chemical clean consisting of about 65 to 70 hours of copper removal and 40 to 45 hours of iron removal was approximately 230 µm although typical corrosion was 10 to 150 µm. Galvanic currents were similar for all coupled specimens. However, the currents measured were clearly different for copper removal, iron removal, and rinse steps. It is recommended that corrosion be monitored during a chemical clean by periodic examination of corrosion test specimens, that galvanic currents be used to monitor solvent conditions and that more tests be done to determine the sensitivity of the current measurement to solvent chemistry.



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## EXECUTIVE SUMMARY

# STEAM GENERATOR CORROSION DURING CHEMICAL CLEANING

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The corrosion of welds, joints, and crevices in steam generator components which would be exposed to chemical cleaning solvents during a Bruce "A" steam generator tubesheet chemical clean was evaluated. The effect of galvanic coupling of welds to the I-600 tube bundle was studied.

Full size corrosion test specimens representing carbon steel, I-600, and stainless steel weld combinations and joints and crevices in identical configurations to what would be found in the steam generator were fabricated. Specimen surfaces which would not normally be exposed to chemical cleaning solvents were masked with an epoxy paint. These specimens were then subjected to a multi-step chemical clean consisting of three copper removal, two iron removal and ten rinse steps at flows expected during a tubesheet chemical clean. Total copper removal duration was 67 hours and total iron removal was 42 hours.

Visual examination and optical microscopy revealed minor corrosion of structural metals after exposures in chemical cleaning test runs. Welds were found to be preferentially attacked to the extent of about two to four times the base metal rate. Further acceleration, to a factor of about five times the base metal rate, occurred at or near the weld fusion line, forming a shallow groove. I-600 was unattacked.

Welds close to I-600 such as the shroud seam, tubesheet to thickshell, blowdown block to shell, shroud foot and blowdown header to shroud welds, with the exception of the thick shell to main shell weld, were the most severely attacked. However, maximum corrosion was approximately 230 µm although typical corrosion varied from 10 to 150 µm. This is comparable to results reported by EPRI.



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The contribution of the galvanic couple to overall attack could not be established from the tests performed since identical uncoupled specimens were not tested.

Galvanic currents were similar for all coupled specimens at any given time during the experiments. However, the currents measured were clearly different for copper removal, iron removal, and rinse steps.

Currents measured during iron removal steps were two to four orders of magnitude larger than currents measured during rinse steps which were greater than currents measured during the first copper removal steps. The "apparent" anodic reaction of I-600 in the copper removal steps occurring after iron removal steps was probably due to removal of copper which plated out on the I-600 in the previous iron removal step. Currents measured during rinse steps after iron removal steps were less than currents measured during rinse steps after copper removal steps.

It is recommended that:

1. corrosion be monitored during a chemical clean by inserting test specimens representing welds, joints, and crevices in the solvent under flow conditions similar to those in the steam generator. These specimens could be examined visually at various stages of the chemical clean.

2. galvanic currents be monitored as they could possibly show conditions which might indicate that accelerated corrosion was taking place e.g. out-of-specification solvent.

3. more tests be done to determine the sensitivity of the current measurement to solvent chemistry since the tests described in this report were done only at the specified solvent and temperature conditions.

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Dr. D. Mills
Director of Research

# STEAM GENERATOR CORROSION DURING CHEMICAL CLEANING

## 1.0 INTRODUCTION

Bruce "A" steam generators have tubesheet sludge piles that are currently estimated to be between 15 and 41 cm maximum depth./1/ These sludge piles may produce an environment conducive to tube corrosion and so removal of the sludge pile would help maintain tube integrity. Chemical cleaning of the tubesheet is one sludge removal option. Corrosion during the chemical clean is a concern since the solvent itself may be corrosive/2/.

The chemical cleaning solvent may be corrosive to welds, crevices and areas where dissimilar metals are in contact. Of particular concern are the welds in the steam generator which are in contact with the solvent. These welds are inaccessible and so cannot be repaired if damaged. It is also difficult to inspect these welds to assess any damage. The amount of galvanic corrosion may depend on geometry and so it may be important to simulate the geometry of the area tested.

## 2.0 PURPOSE

This work was undertaken to investigate the potential for accelerated corrosion of welds, crevices and joints that would be exposed to solvent during the chemical clean of the tubesheet area. This work complements other tests to determine erosion-corrosion during chemical cleaning/3/.

The purpose of the tests described in this report was to expose full-size corrosion test specimens of parts of the steam generator which would be exposed to chemical cleaning solvent, to a multi-step chemical clean consisting of iron and copper removal steps, and to monitor corrosion by measuring the current between different specimens and I-600 tube bundles during the clean. The test specimens were then examined to assess corrosion.

## 3.0 TEST PROGRAM

### 3.1 Equipment

#### 3.1.1 Chemical Cleaning Loop

All tests were performed in the Chemical Cleaning Loop (Figure 1). It is a 316 stainless steel loop with flanged fittings, a 36 L reservoir, a large chamber which housed the corrosion test specimens, and a centrifugal pump. Total solvent volume in the loop was 55 - 60 L for these tests. Maximum flowrate was 2.1 L/s. The system could be purged with nitrogen gas. Temperature was monitored continually. A heater in the reservoir and heater tape around the reservoir heated the loop as required. Water running over the outside of the test chamber cooled the loop as required. In the iron removal step, temperature was controlled by the heaters. In the copper removal step, maximum and minimum temperatures were controlled by the cooling water over the sample chamber and reservoir heaters respectively.

#### 3.1.2 Current Measurement Technique/4/

Some corrosion test specimens were coupled to I-600 tube bundles as explained in section 3.2. The tubes of each bundle simulator were electrically connected to each other by stainless steel wires. A separate wire was spot welded to the weld specimens and the spot welded area was masked off with epoxy paint. All wires were insulated with heat-shrink covers, identified with numbered tags, and brought outside the test chamber.

The corrosion test specimens were electrically connected to the corresponding bundle simulators through relays (HP 3497A option 110 relay actuator card) such that the coupling current could be monitored periodically. An analog zero resistance ammeter (ZRA) (Aardvark model PEC a) was used to monitor currents. Figure 2 shows the wiring arrangement. In operation a command was issued to the HP3497A data acquisition unit to close the two relays corresponding to the channel to be measured, thus placing the ZRA in the circuit. The output signal of the ZRA was then read using the 3497A internal voltmeter and converted to coupling current by use of a manually entered scale factor to accommodate range switching on the ZRA.

### 3.2 Corrosion Test Specimen Fabrication and Preparation

Corrosion test specimens were made to represent all welds, joints and crevices which would be exposed to solvent during a recirculating chemical clean in a steam generator filled to below the first support plate. Table 1 lists the areas selected and materials and weld procedures used. Two sets of coupons were made for two identical experiments to verify experimental reproducibility.

**TABLE 1**

**CORROSION TEST SPECIMENS: SELECTION AND FABRICATION**

| part | materials | electrode type | weld procedure | I-600 couple |
|---|---|---|---|---|
| **Pressure Vessel Welds** | | | | |
| tubesheet/ thickshell | SA-105 Gr 2 to SA-516 Gr 70 | RACO 128 | 210257 210273 | yes |
| blowdown block/shell | A-36/ SA-516 Gr 70 | E7015A1 E7018A1 | 210260 | yes |
| blowdown nozzle/shell | SA-105 Gr 2/ SA-516 Gr 70 | E7015A1 | 210260 | no |
| blowdown tube/shell | I-600/ SA-516 Gr 70 | I 182 | 210133 | no |
| thick shell/ main shell | SA-516 Gr 70 | Oxweld 65 | 210273 | yes |
| shroud pin assembly | SA-105 Gr 2/ SA-516 Gr 70 | E7015A1 E7018A1 | 210260 | no |
| **Internal Welds** | | | | |
| shroud foot | A-36/ SA-516 Gr 70 | E7015A1 E7018A1 | 210260 | yes |
| locking tab | 304SS/A36 | | TIG | yes |
| shroud seam | SA-516 Gr 70 A36 | E7015A1 E7018A1 | 210260 | yes |
| blowdown header/shroud | A-36/ SA-516 Gr 70 | E7015A1 | 210260 | yes |
| blowdown piping | I-600 | I-182 | 210253 | no |
| **Joints/Crevices (no welding)** | | | | |
| tie rod and sleeve | SAE Gr 5 bolt 106 Gr B pipe, in SA-105 Gr 2 | | | no |
| tube in sleeve | I-600 SA-105 Gr 2 | | | yes |

The coupons were manufactured by B&W Canada using archival material from Bruce "A". Surface preparation was similar to what was done at the station. All surfaces of a weld sample which would not normally be exposed to the solvent were masked with epoxy paint.

When required, the presence of the tube bundle was simulated by positioning a group of tube sections near or around the corrosion test specimen/4/. Eight specimens were provided with bundle simulators. Table 1 shows which welds were coupled with I-600 and Figure 3 shows the welds coupled to the I-600 bundles.

A separate experiment was conducted to determine the optimal arrangement for the bundle simulator/4/. In this experiment, a piece of steel, similar in size to the weld specimens, was immersed in a citric acid solution and coupled to different numbers of I-600 tubes while monitoring the resulting galvanic current. Results showed that twelve tubes were the minimum required since additional tubes had little effect on coupling current. The coupling current was found to vary very little with the relative distance between the steel and the tubes and so a separation distance of 2 to 3 cm was chosen to provide for a compact sample arrangement.

For most simulations, twelve I-600 steam generator tubes, about 10 cm long each, were arranged as three rows of four tubes in a triangular pitch arrangement. The tubes were spaced from each other and held together by self-locking nylon wire ties. Bundle simulators were spaced about 2 to 3 cm from the weld specimens with teflon blocks to ensure correct proximity and avoid unintentional electrical contact. Each assembly was held together by self-locking nylon wire ties.

### 3.3 Experimental Program

Each set of 12 corrosion test specimens was subjected to a multi-step chemical clean in the chemical cleaning loop. The corrosion test specimens were inserted into the chamber as shown in Figure 4. Sludge was added to the loop throughout the experiment so that the coupons would be exposed to dissolved metals in the solvent. Table 2 shows the step sequence for each test; Table 3 shows solvent composition; Table 4 shows the experimental conditions; and Table 5 shows the sludge composition. The duration of each step was determined arbitrarily, not by the rate of metal dissolution, and varied from 20 to 23 hours.

**TABLE 2**

**CHEMICAL CLEAN STEP SEQUENCE (BOTH RUNS)**

Cu1 / R1 / R2 / Fe1 / R3 / R4 / (add sludge) Cu2 / R5 / R6 / (add sludge) Fe2 / R7 / R8 / Cu3 / R9 / R10

Steps:

| | |
|---|---|
| Cu# | copper removal |
| R# | rinse |
| Fe# | iron removal |

**TABLE 3**

**CHEMICAL CLEANING SOLVENT COMPOSITION**

| Copper Removal Solvent | Iron Removal Solvent | Rinse |
|---|---|---|
| 5% EDTA | 10% EDTA | $NH_3$ to |
| 3% En (pH 9 - 9.5) | 1% $N_2H_4$ | pH 10 |
| 2% $H_2O_2$ | $NH_3$ to pH7 | |
| | 0.75% CCI-801 | |
| | 20 mg/L H-10 defoamer | |
| | $N_2$ cover gas | |

**TABLE 4**

**EXPERIMENTAL CONDITIONS**

| | | |
|---|---|---|
| Sludge | : | 1 kg Lakeview/Nanticoke mixture in reservoir<br>500 g added at beginning of each of 2nd Cu & Fe removal steps |
| Steel Wool | : | 45.1 g Bull Dog brand coarse steel wool in reservoir |
| Temperature | : | copper removal 70 to 82 $^{o}$F (21 to 28 $^{o}$C)<br>iron removal 200 $^{o}$F (93.3 $^{o}$C) |
| Flow Rates | : | copper and iron removal steps - 2.1 L/s (~10 cm/s)<br>rinse steps - 0.5 L/s (~2.5 cm/s) |

Hydrogen peroxide was added three times in each copper removal step; at the beginning, at 2 to 3 hours, and at 4 to 6 hours.

Steel wool was added to preserve a carbon steel surface area to solvent volume ratio representative of the steam generator.

**TABLE 5**

**SLUDGE COMPOSITION**

| element | g/kg |
|---|---|
| Fe | 385 |
| Cu | 316 |
| Ni | 75.5 |
| Zn | 27.3 |
| Mg | 0.57 |
| Ca | 0.24 |
| Na | 0.11 |
| K | 0.02 |
| Al | <1 |
| Si | <1 |
| total | 804.74 |

### 3.4 Sampling and Analysis

The solvent was sampled daily and analyzed for dissolved iron and copper, and pH.

### 3.5 Corrosion Test Specimen Post-Test Examination/4/

After the chemical clean, samples were removed from the test chamber, cleaned, dried, visually examined, and photographed by Metallurgy to record their general condition. In recording the extent of corrosion, the term superficial is used to indicate attack that did not obscure details of the original surface condition, was very shallow, or was sparsely distributed. The term shallow is used to indicate attack that was general enough to obscure surface details or was somewhat deeper than superficial. The terms are used subjectively, but roughly correspond to attack depth as follows.

superficial: 10 µm to 30 µm

shallow: 40 µm to 70 µm

Selected samples were cross-sectioned to enable estimates to be obtained of the extent of degradation. The amount of corrosion on these samples is generally representative of the more severely corroded welds.

Estimation of the amount of corrosion was hampered by the size of the samples and by the roughness of the original surfaces. In particular, weld beads do not provide a good reference surface for the determination of depth of attack because of their roughness and non-uniformity. The approach adopted is outlined below.

1. Obtain photographs of representative cross-sections of samples both before and after test, at a magnification that reveals sufficient detail of the surface profile to both see the extent of attack and to make measurements.

2. Estimate smooth surface profiles for each section. In the case of corroded samples, an attempt was made to position the profile at the original surface location.

3. Measure the distance between the smooth surface line and the actual metal surface at various locations on the profile to obtain an approximate maximum deviation from the profile. For unexposed samples, the maximum deviation represents the original surface roughness, whereas for cleaned sample it is taken as the sum of the original roughness and the amount of corrosion.

4. Using the data obtained in steps 1 to 3 and the general assessments, estimate the depth of corrosion attack.

## 4.0 RESULTS AND DISCUSSION

### 4.1 Chemistry

Dissolved iron and copper concentration increased with time for iron and copper removal steps respectively. Table 6 shows the dissolved metal concentrations at the end of each metal dissolution step. Both runs had similar dissolution rates for each step. Maximum copper concentrations varied from 5.6 g/L in the first copper removal step to 2.0 g/L in the third copper removal step. Maximum iron concentrations at the arbitrarily determined end of each step varied from 2.5 to 3.7 g/L representing about 60 to 70% removal of available iron in the sludge.

**TABLE 6**

**DISSOLVED IRON AND COPPER CONCENTRATIONS AT THE END OF EACH CHEMICAL CLEANING STEP**

| | Run 1 | | Run 2 | |
|---|---|---|---|---|
| | Cu g/L | Fe g/L | Cu g/L | Fe g/L |
| Cu1 | 5.56 | n.a. | 4.6 | n.a. |
| Cu2 | 2.86 | n.a. | 2.74 | n.a. |
| Cu3 | 2.19 | n.a. | 1.97 | n.a. |
| Fe1 | n.a. | 3.16 | 0.001 | 3.10 |
| Fe2 | 0.05 | 2.49 | 0.027 | 3.67 |

Changes in pH are shown in Table 7. The pH in copper removal steps generally decreased from 9.1 - 9.7 to 8.1 - 8.5. The pH in iron removal steps changed from 6.9 - 7.1 to 7.1 - 7.4. The pH decreased during all copper removal steps. The pH increased in all but one iron removal step.

**TABLE 7**

**VARIATION OF PH THROUGHOUT CHEMICAL CLEANING RUNS**

| | Run 1 | | | Run 2 | | |
|---|---|---|---|---|---|---|
| | initial | final | duration hours | initial | final | duration hours |
| Cu1 | 9.1 | 8.5 | 23 | 9.2 | 8.3 | 21.5 |
| Cu2 | 9.3 | 8.1 | 21.7 | 9.2 | 8.2 | 23.0 |
| Cu3 | 9.7 | 8.2 | 22.4 | 9.4 | 8.1 | 22.8 |
| Fe1 | 7.1 | 7.4 | 21.5 | 6.9 | 7.3 | 21.4 |
| Fe2 | 7.1 | 7.1 | 21.0 | 7.1 | 7.4 | 20.5 |

## 4.2 Current Measurements

Figure 5 shows a typical variation in current with time for a coupled specimen./4/ The logarithm of the current is plotted against time. The upper portion represents the corrosion test specimen as being cathodic and the I-600 as anodic (i.e. "corroding") while the lower portion represents the corrosion test specimen as being anodic and the I-600 as cathodic.

Galvanic currents were similar for all coupled specimens at any given time during the experiment. Some apparent differences

resulted from poor or intermittent electrical contact. However, the currents measured were clearly different for copper removal, iron removal, and rinse steps.

On all corrosion test specimens, the specimens were anodic for the first copper removal step and all rinses and iron removal steps. Instances of reversed current during the second and third copper removal steps may have been a result of dissolution of copper deposited on the I-600 tubing during the previous iron removal step.

Anodic galvanic currents were about two orders of magnitude greater for iron removal steps than for rinse steps which were greater than the first copper removal step. The current measured during a rinse after an iron removal step was always less than that measured during a rinse after a copper removal step. The current measured during the first copper removal step always decreased at least one order of magnitude throughout the step.

The contribution of the galvanic couple to overall attack could not be established from the tests performed since no tests were performed on identical specimens without galvanic coupling.

Figure 6 shows the current measured for all specimens during the first copper removal step in Run 2. Each $H_2O_2$ addition took approximately 45 minutes. The first addition was completed before current measurements were started at which time the current was decreasing with time. The current increased as soon as the second $H_2O_2$ addition started. The third addition started about 20 minutes after the second addition was finished and resulted in a further increase in current. The current reached a maximum about 1 1/4 hours after completion of the third addition and decreased thereafter to about half the maximum value.

This behaviour was observed on all but three specimens in Run 2, and on all specimens in Run 1. Data was not available for plotting Run 1 in the same way. The maximum current density observed was calculated to be on the order of 3 $\mu A/cm^2$ which would roughly correspond to an iron corrosion rate of about 0.04 $nmoles.cm^{-2}.s^{-1}$. This corrosion rate, if sustained throughout a 24 hour copper removal step, would amount to an average penetration of about 0.2 µm.

Therefore while an increase in hydrogen peroxide concentration may appear to increase the galvanic current of carbon steel, the current is negligible compared to currents resulting from the iron removal steps.

### 4.3 Test Specimen Corrosion

Visual examination and optical microscopy revealed minor corrosion of structural metals after exposures in chemical cleaning test runs. The I-600 appeared unattacked. Table 8 summarizes the results of visual inspection of the corrosion test specimens. Figures 7 to 24 illustrate the corrosion test specimens before and after chemical cleaning. Table 9 summarizes the corrosion measurements made by Metallurgy/4/.

Corrosion test specimens coupled to I-600 experienced greater corrosion than those not coupled to I-600 with the exception of the thick shell to main shell, locking tab, and tube-in-sleeve specimens. The latter two specimens were not carbon steel to carbon steel welds and the thick shell to main shell weld used a different electrode type (Oxweld 65) than the other welds. These results are comparable to EPRI work in which welds with carbon steel or low alloy filler metal suffered the highest corrosion rates when coupled to I-600/5/.

The blowdown header to shroud, shroud seam, shroud foot, blowdown block to shell, and tubesheet to thick shell welds, all coupled to I-600, appeared to be the most susceptible to preferential attack. These welds were selected for further examination and corrosion depth estimation after cross-sectioning. They were found to be preferentially attacked to the extent of about twice to four times the rate of the base materials. Further acceleration, to a factor of about five times the base metal rate, occurred at or near the weld fusion line, forming a shallow groove. The maximum extent of corrosion was approximately 230 µm although corrosion was typically about 10 to 150 µm as a result of the chemical clean. This is comparable to the results of the CATS tests which consisted of single 50 hour iron removal steps in which the maximum corrosion for the same inhibitor concentration, 0.75% CCI-801, was about 200 µm/5/.

It is evident that the weld metal is anodic to the base metals, except in the case of the locking tab, which employs an alloy weld filler/4/. However, under the conditions of exposure, this leads to only a small increase in the rate of corrosion compared to the parent metals, even with the increased cathode area provided by the coupled alloy tube bundle.

Although the results agreed with the EPRI results, the concentration of dissolved iron (2-3 g/L) was lower than the 10-12 g/L reported in the EPRI tests. Galvanic corrosion appears to be proportional to the iron oxide dissolution /6/ and so could have been higher if dissolved iron concentrations had been higher. Thus corrosion may be higher during a chemical clean at Bruce NGS "A" because it is expected that about 6 iron removal steps, each attaining a dissolved iron concentration of up to 10-12 g/L, may be performed.

## TABLE 8

### SUMMARY OF CORROSION ASSESSMENTS OF CORROSION TEST SPECIMENS AFTER CHEMICAL CLEANING

| NAME | | GENERAL OBSERVATIONS |
|---|---|---|
| **Pressure Vessel Welds** | | |
| Tubesheet to Thick Shell * | base metal | superficial general corrosion |
| | weld | shallow non-uniform preferential attack with further acceleration of attack at the fusion line |
| Blowdown Block to Shell * | base metal | superficial general corrosion with surface features still visible; some scattered pits |
| | weld | shallow non-uniform preferential attack with further acceleration of attack at fusion line; some of weld bead unattacked in run 1 but all of weld bead attacked in run 2 |
| Nozzle to Shell | base metal | scattered superficial pitting of tube bore |
| | weld | general non-uniform preferential weld attack |
| Blowdown Tube to Shell and Tube to Tube | base metal | superficial attack of the bore of the shell penetration |
| | weld | no corrosion of tube or tube-to-tube welds |
| | crevice | no attack |
| Thick Shell to Main Shell | base metals | non-uniform superficial corrosion |
| | weld | slight grooving at fusion line in run 2 |
| Shroud Pin | base metals | general superficial corrosion; very minor attack on bore of shell penetration and on shroud pin in run 2 |
| | crevice | no attack |

**Internal Welds**

| | | |
|---|---|---|
| Shroud Foot * | base metals | non-uniform superficial corrosion |
| | weld | shallow general preferential attack with loss of surface features |
| Locking Tab | base metal | superficial corrosion (run 1)<br>very shallow non-uniform corrosion (run 2) |
| | tab | unattacked; no crevice corrosion under tab |
| | tab<br>weld | unattacked |
| Shroud Seam * | shroud | shallow, non-uniform, general attack |
| | weld | preferential attack with general loss of surface features and slight further acceleration of attack at weld fusion line |
| Blowdown Header to Shroud * | base metal | unattacked, machining marks visible |
| | weld | shallow non-uniform attack more apparent in run 2 than in run 1; surface features still visible |

**Joints-Crevices (no welding)**

| | | |
|---|---|---|
| Tie-Rod and Sleeve | | superficial corrosion only |
| Tube in Sleeve | base metals | tube unattacked;<br>superficial non-uniform attack on sleeve;<br>scattered small pits in run 2 |

* greatest attack: selected for cross-sectioning and corrosion depth measurement

**TABLE 2**

**ESTIMATES OF CORROSION DEPTH ON WELD CORROSION SPECIMENS AFTER CHEMICAL CLEANING**

| WELD NAME | | MEASUREMENTS µm | | CORROSION ESTIMATES µm |
|---|---|---|---|---|
| | | before | after | |
| Shroud Seam | weld | 40-124 | 170-353 | 130-230 |
| | shroud | 50 | 88-115 | 60 |
| Tubesheet to Thickshell | base metal | 0 | 22-35 | 22-35 |
| | weld | 0 | 40-74 | 40-74 |
| | fusion line | 0 | 130-154 | 130-154 |
| Blowdown Block to Shell | base metal | 50-86 | 70-90<br>92-134 pits | 10-20<br>40-50 pits |
| | weld | 43-70 | 80-110 | 40 |
| | fusion line | 87-190 | 205-276 | 80-100 |
| Shroud Foot | weld | 30-55 | 95-194 | 65-140 |
| Blowdown Header to Shroud | weld | 22-40 | 95-124 | 75 |

## 5.0 SUMMARY

Currents measured during iron removal steps were two to four orders of magnitude larger than currents measured during rinse steps which were greater than currents measured during the first copper removal steps. The "apparent" anodic reaction of I-600 in the copper removal steps occurring after iron removal steps was probably due to removal of copper which plated out on the I-600 in the previous iron removal step. The I-600 tubes appeared unattacked. Currents measured during rinse steps after iron removal steps were less than currents measured during rinse steps after copper removal steps.

Welds were preferentially attacked at two to four times the rates of base metals. Attack of about five times the base metal rate

occurred at or near the weld fusion line. Shroud seam, tubesheet to thickshell, blowdown block to shell, shroud foot, and blowdown header to shroud welds were the most severely attacked. All of these welds were coupled to I-600. However, maximum corrosion was approximately 230 μm although typical corrosion varied from 10 to 150 μm as a result of a chemical clean of 67 hours of copper removal and 42 hours of iron removal. Results were comparable to those reported by EPRI/5/.

## 6.0 CONCLUSIONS

1. Galvanic currents were similar for all coupled specimens at any given time during the experiments. However, the currents measured were clearly different for copper removal, iron removal, and rinse steps.

2. Maximum corrosion resulting from a single chemical clean consisting of about 65 to 70 hours of copper removal and 40 to 45 hours of iron removal was approximately 230 μm although typical corrosion varied from 10-150 μm. I-600 was unattacked.

3. Welds in close proximity to I-600 such as the shroud seam, tubesheet to thickshell, blowdown block to shell, shroud foot, and blowdown header to shroud welds with the exception of the thick shell to main shell weld are likely to be the most severely attacked during a chemical clean.

## 7.0 RECOMMENDATIONS

It is recommended that:

1. corrosion be monitored during a chemical clean by inserting test specimens representing welds, joints, and crevices in the solvent under flow conditions similar to those in the steam generator. These specimens could be examined visually at various stages of the chemical clean.

2. galvanic currents be monitored as they could possibly show conditions which might indicate that accelerated corrosion was taking place e.g. out-of-specification solvent.

3. more tests be done to determine the sensitivity of the current measurement to solvent chemistry since the tests described in this report were done only at the specified solvent and temperature conditions.

## 8.0 ACKNOWLEDGMENTS

The design and operation of the galvanic current measurement system/4/, metallurgical examination/4/, and coordination of the corrosion test specimen fabrication were carried out by the Corrosion and Tritium Technology Section in the Metallurgical Department.

The author would like to acknowledge P. King for designing and performing the current measurements and metallographic examination of the corrosion test specimens, B. Warr for co-ordinating the sample fabrication, P. Leung for performing the experiments, and B. Guest for examining and photographing the corrosion test specimens.

Approved by:

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Manager
Chemical Research Dept

Prepared by:

A.M. McKay
Engineer
Corrosion Chemistry Section
Chemical Research Dept

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2. McSweeney, P., "A Chemical Cleaning Solvent for Removing Magnetite from Steam Generator Deposits", Ontario Hydro Research Division, Report No. 86-347-H, April 16, 1987.

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5. MPR Associates, Inc., Babcock & Wilcox, Combustion Engineering, Inc., Westinghouse Electric Corporation, Weld Region Corrosion During Chemical Cleaning of PWR Steam Generators Volumes 1 & 2, EPRI NP-5267, July, 1987.

6. McSweeney P., personal communication.

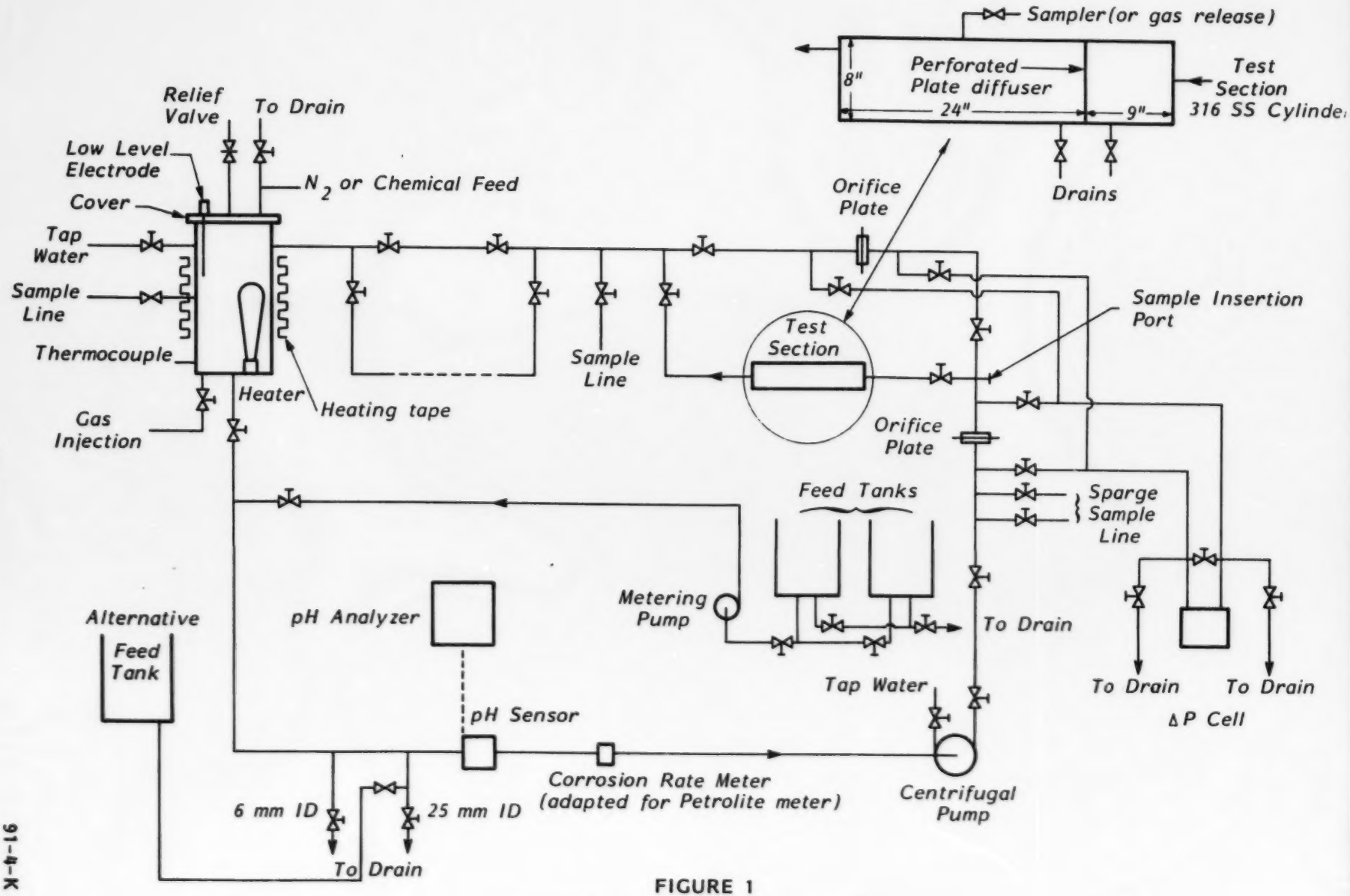



FIGURE 1
CHEMICAL CLEANING TEST LOOP



91-4-K
169781 RD

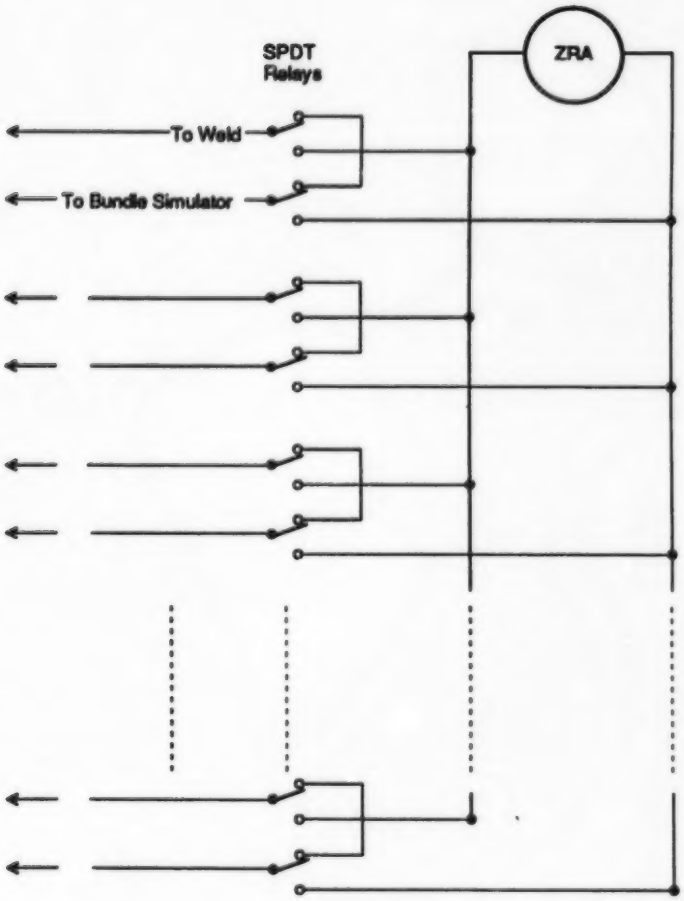
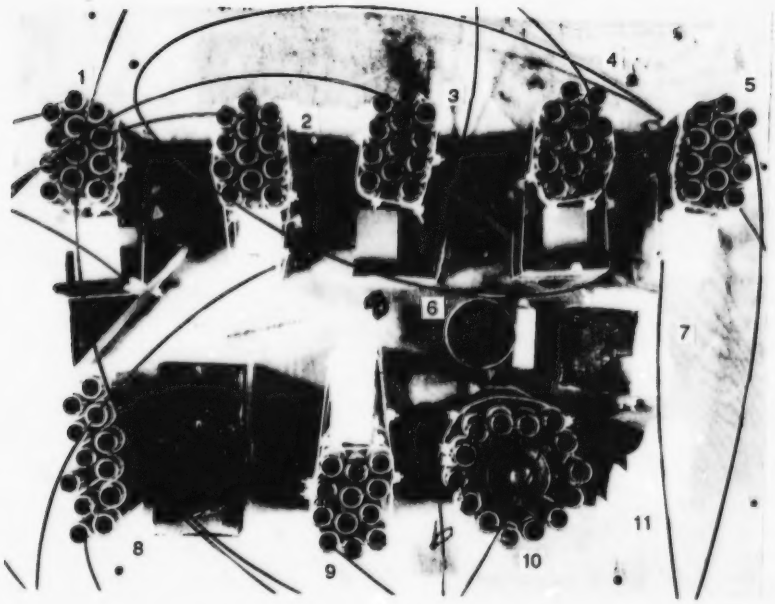
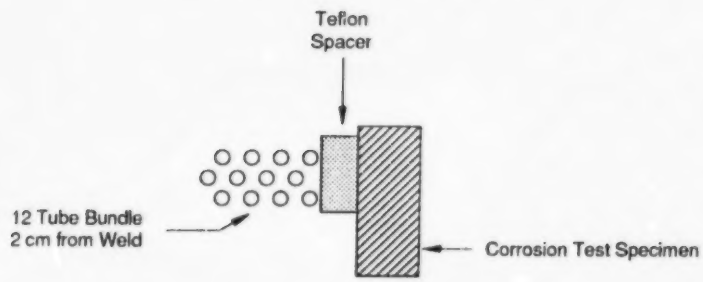



**FIGURE 2**

**WIRING ARRANGEMENT FOR GALVANIC CURRENT MEASUREMENTS**
**(From Ref. 4)**




| | |
|---|---|
| 1 | Blowdown Header to Shroud |
| 2 | Shroud Seam |
| 3 | Blowdown Block to Shell |
| 4 | Shroud Foot |
| 5 | Tube Sheet to Thick Shell |
| 6* | Tube in Sleeve |
| 7* | Shroud Pin Assembly |
| 8 | Locking Tab |
| 9 | Thick Shell to Main Shell |
| 10 | Tie Rod and Sleeve |
| 11* | Blowdown Nozzle to Shell |

* No Coupling

**FIGURE 3**

**I-600/CORROSION TEST SPECIMEN COUPLING CONFIGURATIONS**

91-4-K

184964-G32-RD

A. Thick Shell to Main Shell Weld
B. Blowdown Block to Shell Weld
C. Shroud Seam Weld
D. Locking Tab Weld
E. Tie Rod and Sleeve
F. Blowdown Header to Shroud Weld
G. Shroud Foot Weld
H. Tube Sheet to Thick Shell Weld
I. Shroud Pin Weld
J. Blowdown Tube to Shell and Tube to Tube Welds
K. Nozzle to Shell Welds
L. Tube in Sleeve

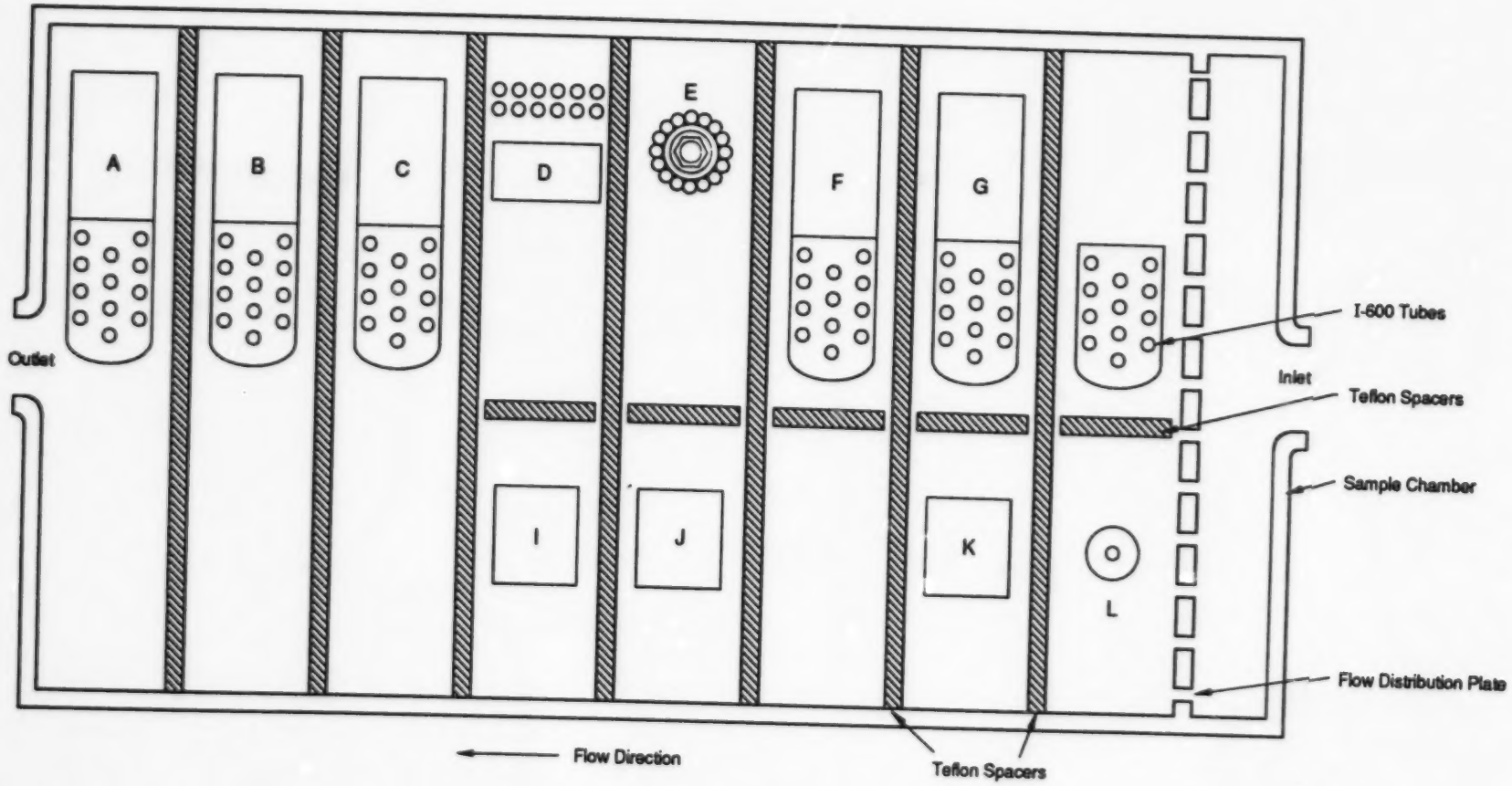



**FIGURE 4**

**CORROSION TEST SPECIMEN PLACEMENT IN TEST CHAMBER (PLAN VIEW)**

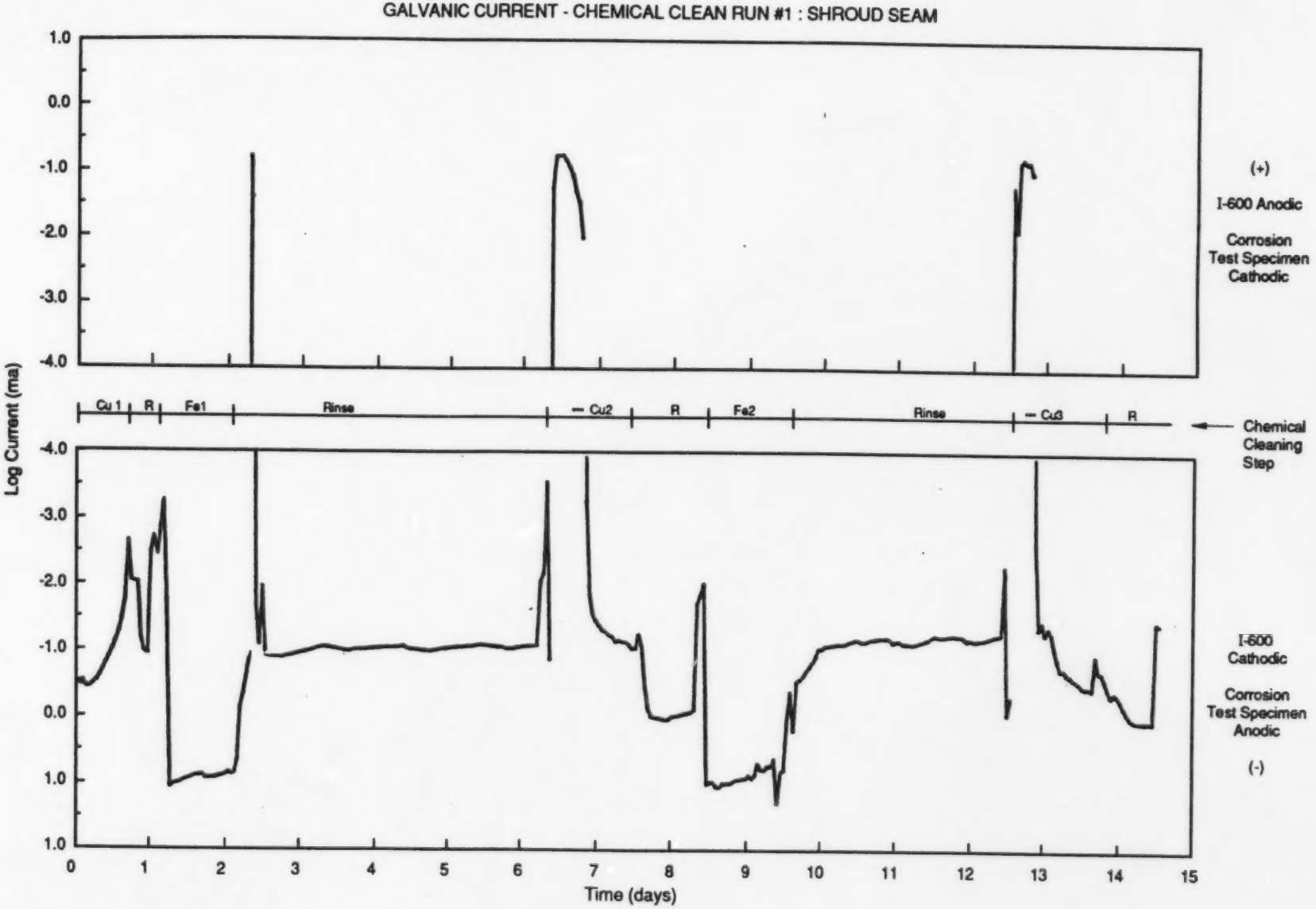



**FIGURE 5**

**TYPICAL VARIATION OF GALVANIC CURRENT WITH TIME (from Ref. 4)**

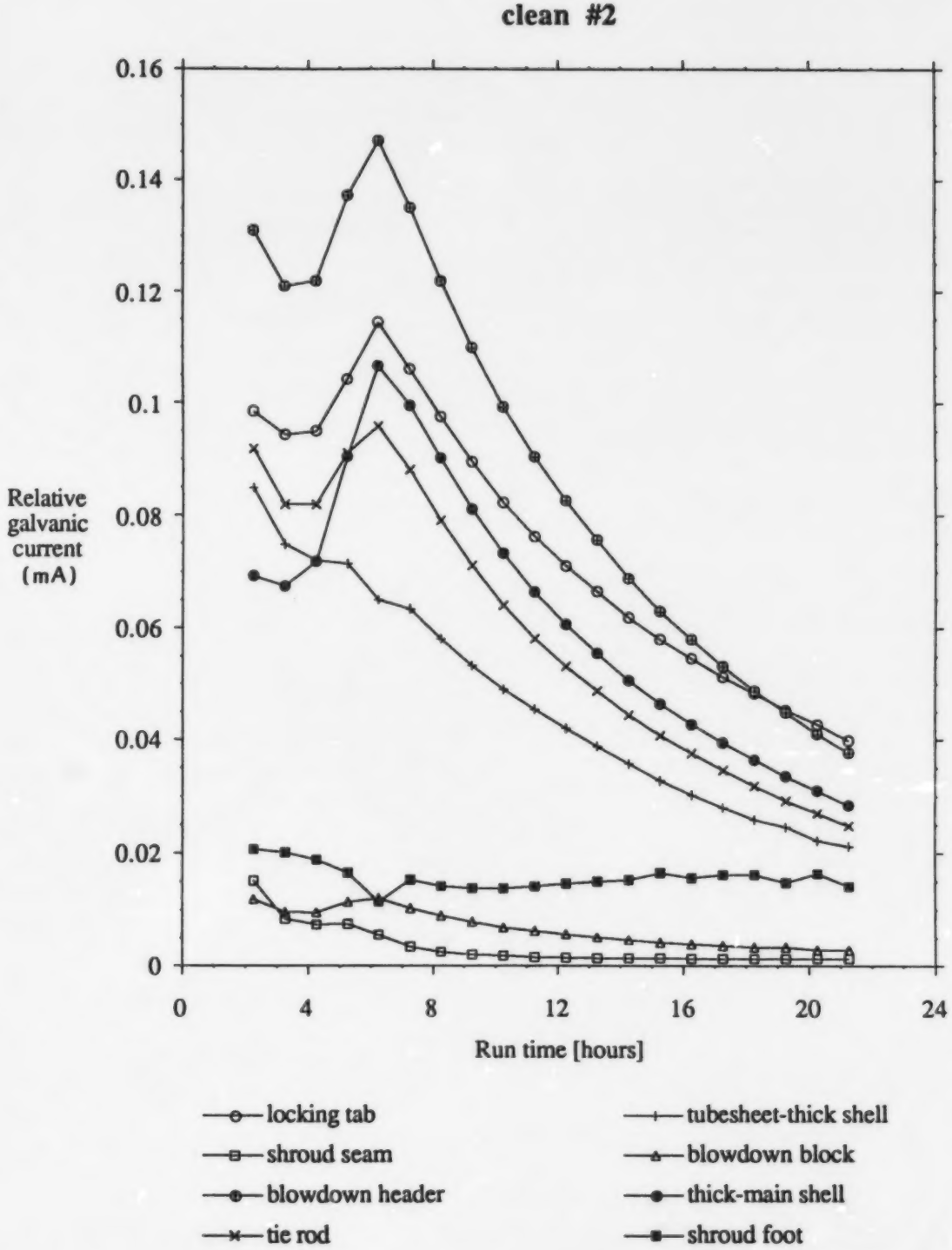



FIGURE 6

VARIATION OF GALVANIC CURRENT WITH TIME DURING FIRST COPPER REMOVAL STEP (FROM REF. 4)

Before Chemical Cleaning

After Chemical Cleaning

**FIGURE 7**

**TUBESHEET TO THICKSHELL CORROSION TEST SPECIMEN**

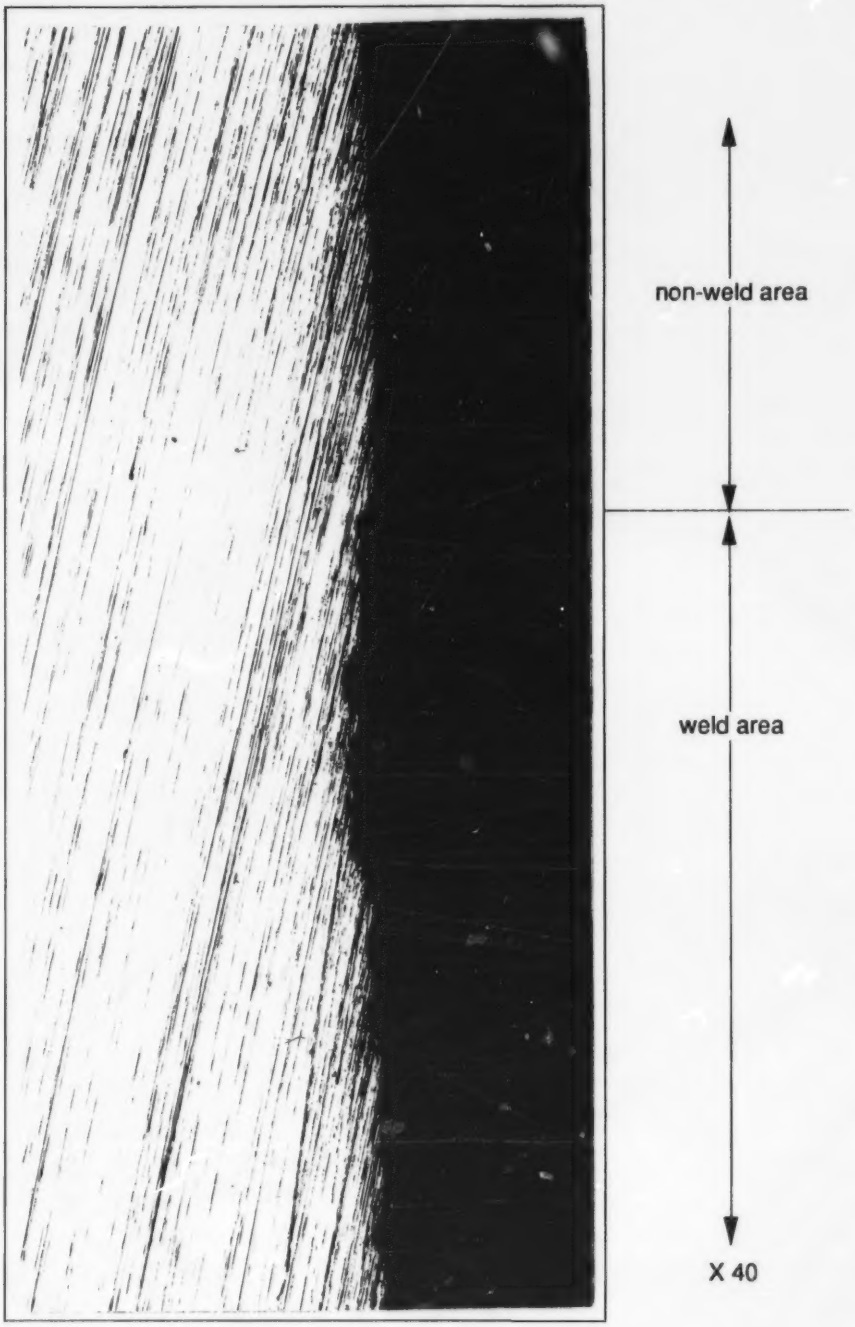
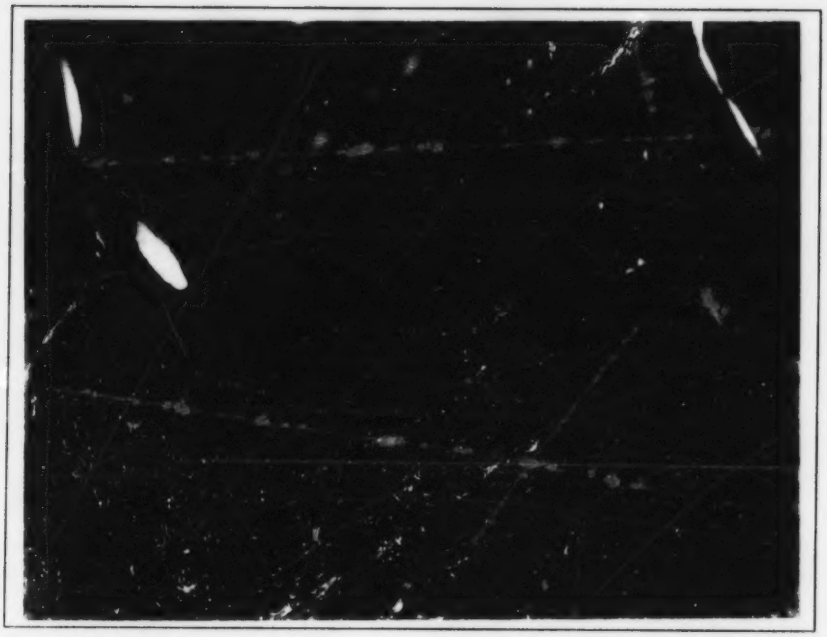



**FIGURE 8**

**TUBESHEET TO THICKSHELL WELD
AFTER CHEMICAL CLEANING**

91-4-K
184889-K14-RD

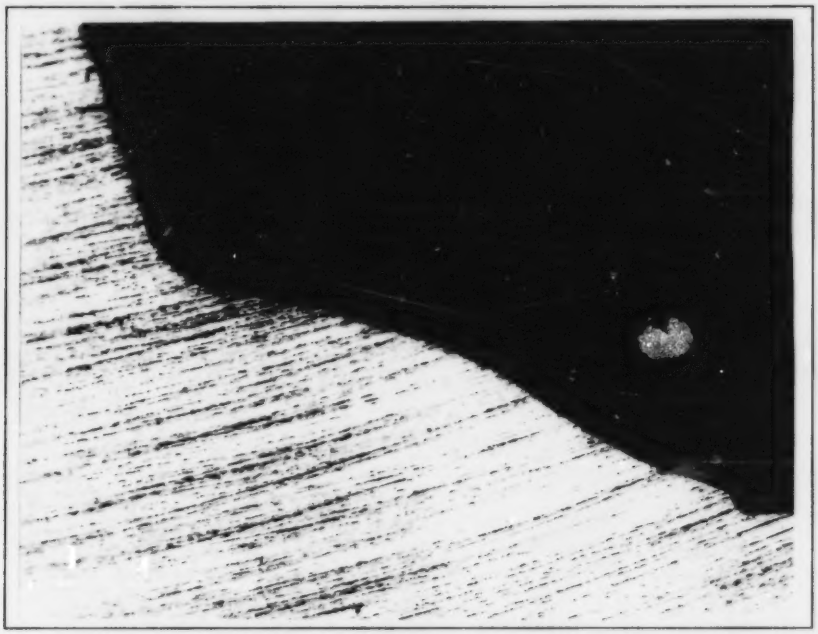


Before
Chemical
Cleaning

After
Chemical
Cleaning

**FIGURE 9**

**BLOWDOWN BLOCK TO SHELL
CORROSION TEST SPECIMEN**



Before
Chemical
Cleaning

X 12.8

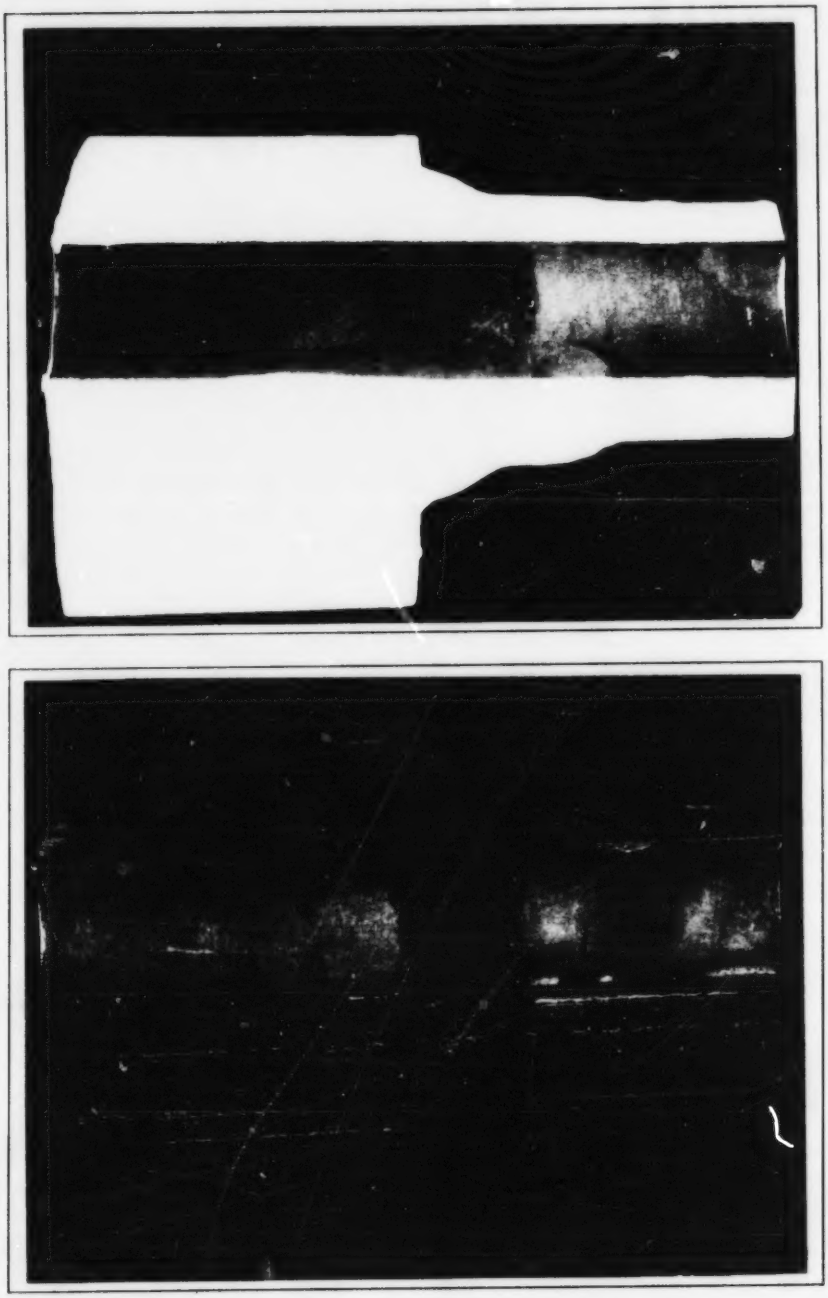
After
Chemical
Cleaning

X 12.8

**FIGURE 10**

**BLOWDOWN BLOCK TO SHELL WELD**

91-4-K
184891-K14-RD



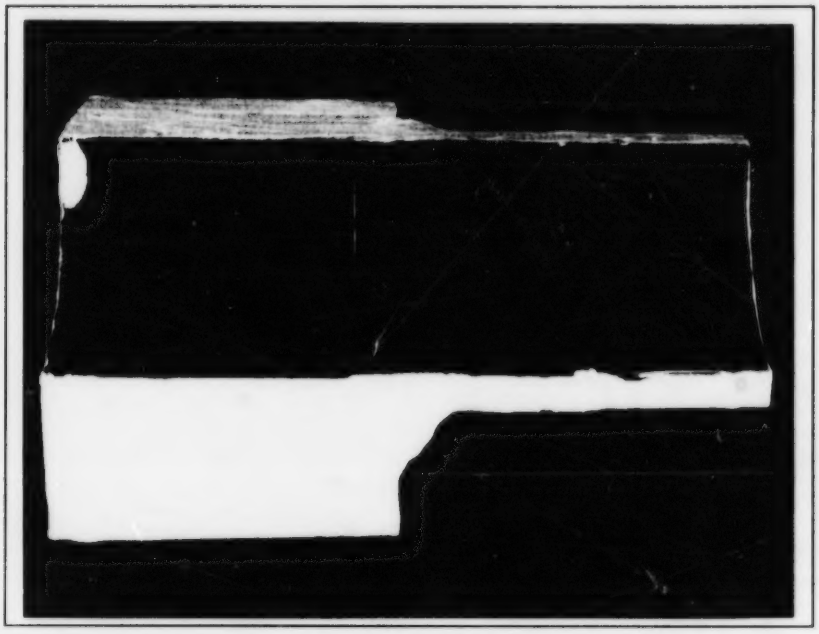
Before Chemical Cleaning

After Chemical Cleaning

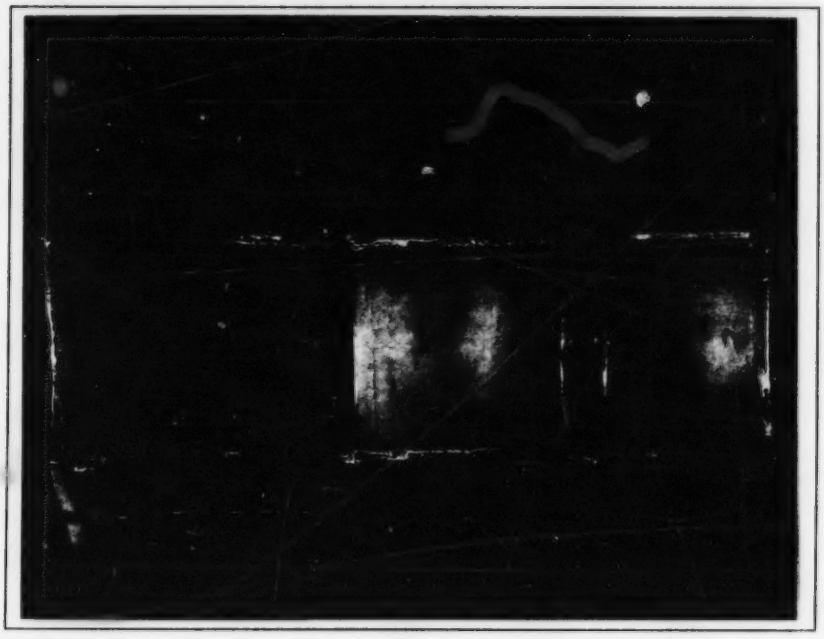
**FIGURE 11**

**BLOWDOWN NOZZLE TO SHELL WELD CORROSION TEST SPECIMEN**

91-4-K
184892-K14-RD



Before
Chemical
Cleaning

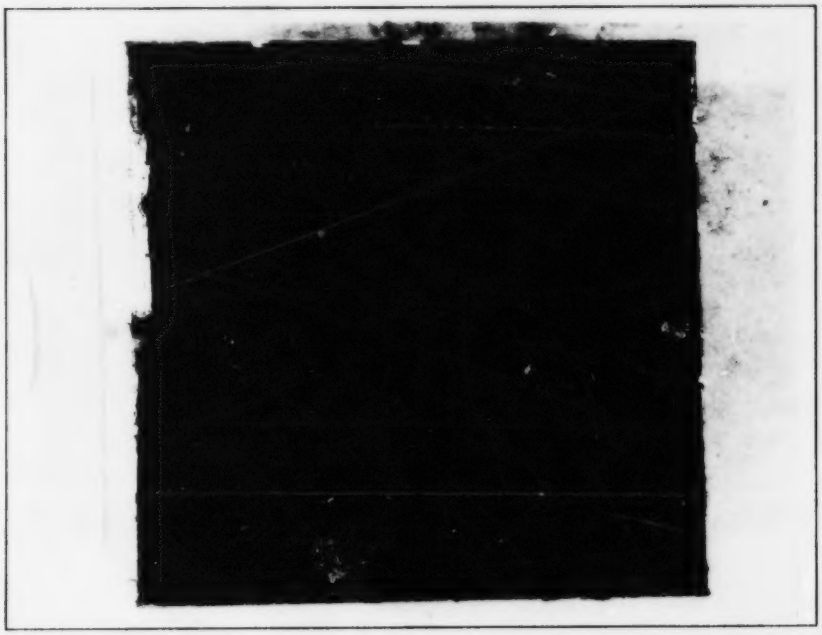


After
Chemical
Cleaning

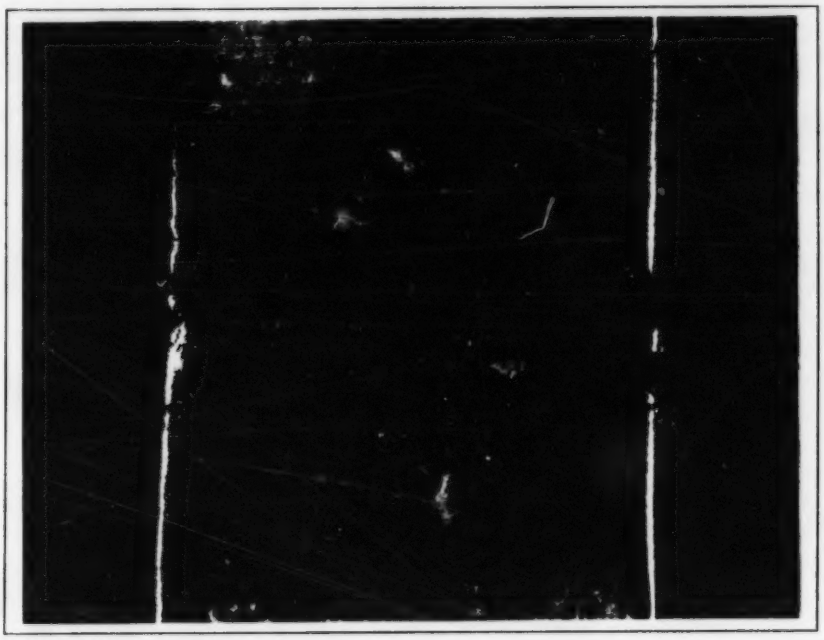
**FIGURE 12**

**BLOWDOWN TUBE TO SHELL AND TUBE TO TUBE WELD
CORROSION TEST SPECIMEN**

91-4-K
184893-K14-RD



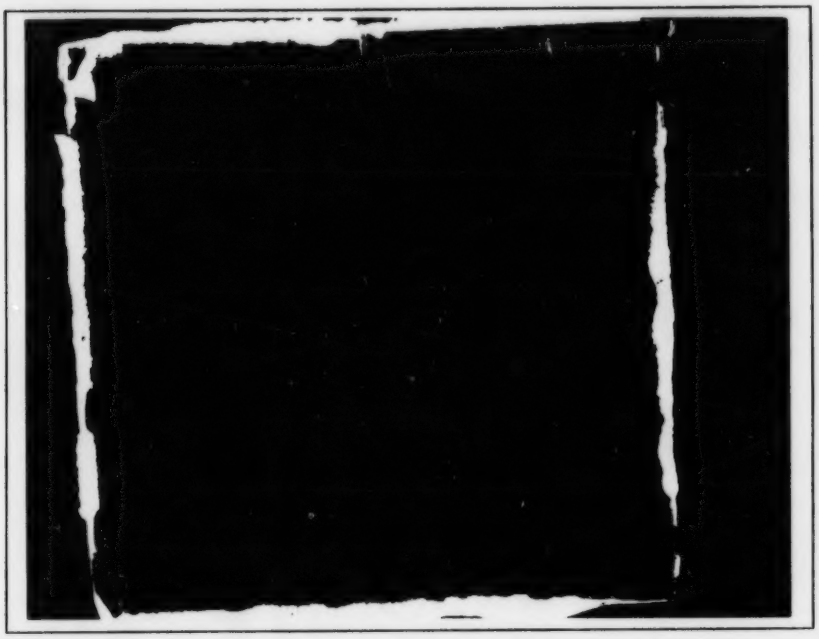
Before Chemical Cleaning



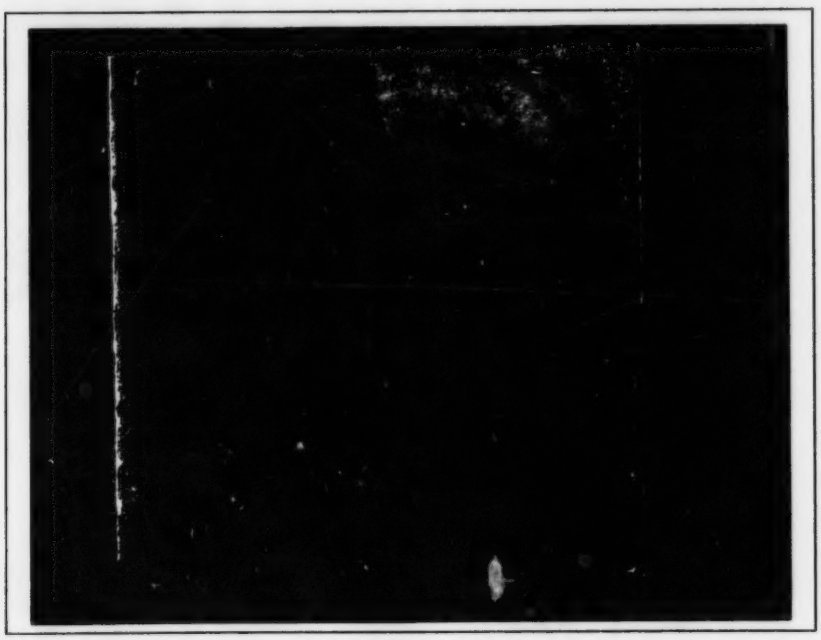
After Chemical Cleaning

**FIGURE 13**

**THICKSHELL TO MAINSHELL CORROSION TEST SPECIMEN**



Before Chemical Cleaning

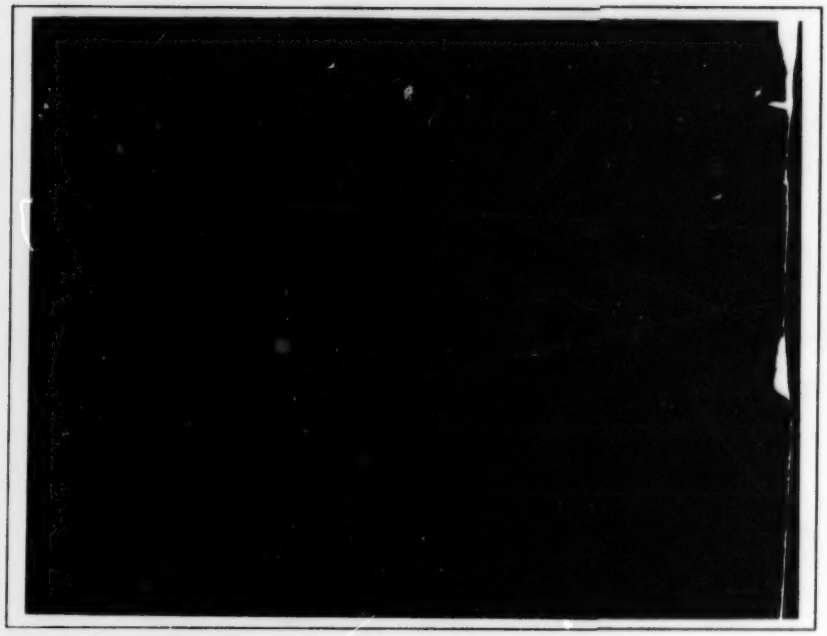


After Chemical Cleaning

**FIGURE 14**

**SHROUD PIN CORROSION TEST SPECIMEN**

91-4-K
184895-K14-RD



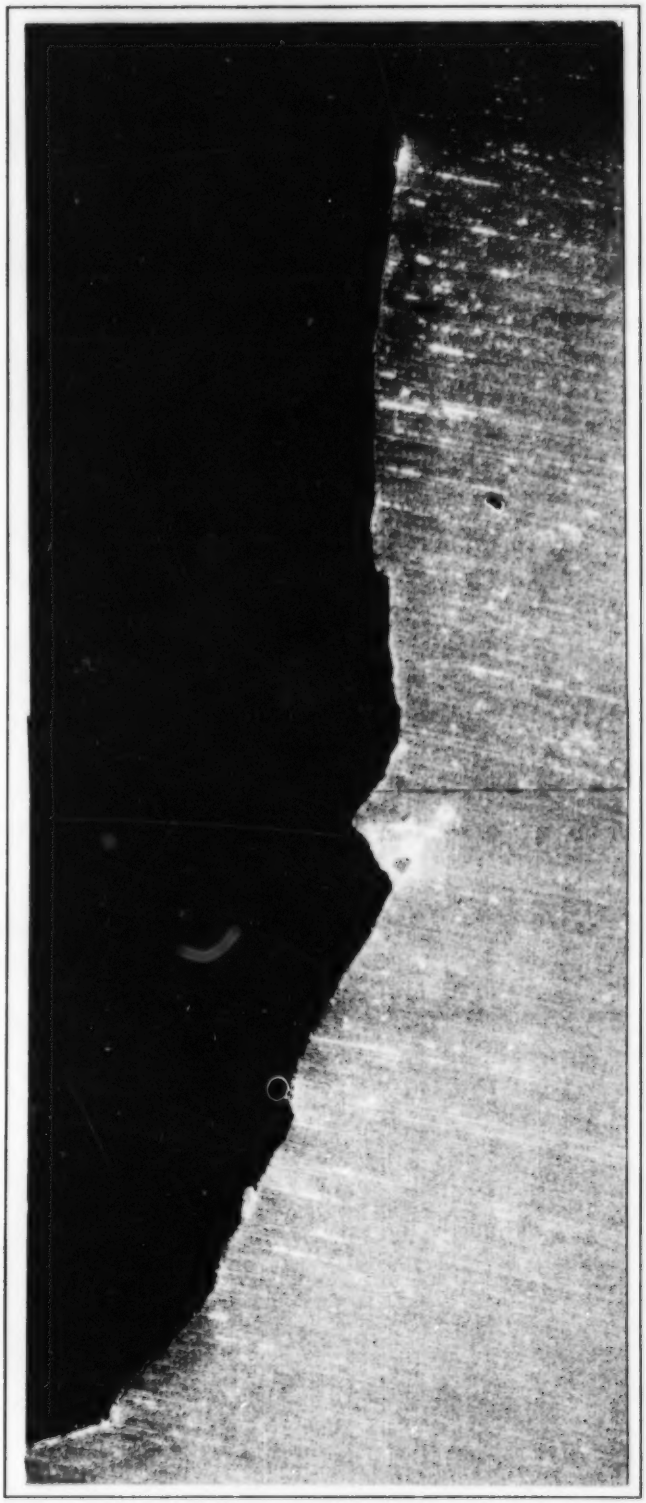
Before Chemical Cleaning

After Chemical Cleaning

**FIGURE 15**

**SHROUD FOOT CORROSION TEST SPECIMEN**

91-4-K
184896-K14-RD



X 30

**FIGURE 16**

**SHROUD FOOT WELD BEFORE CHEMICAL CLEANING**

91-4-K
184897-K14-RD

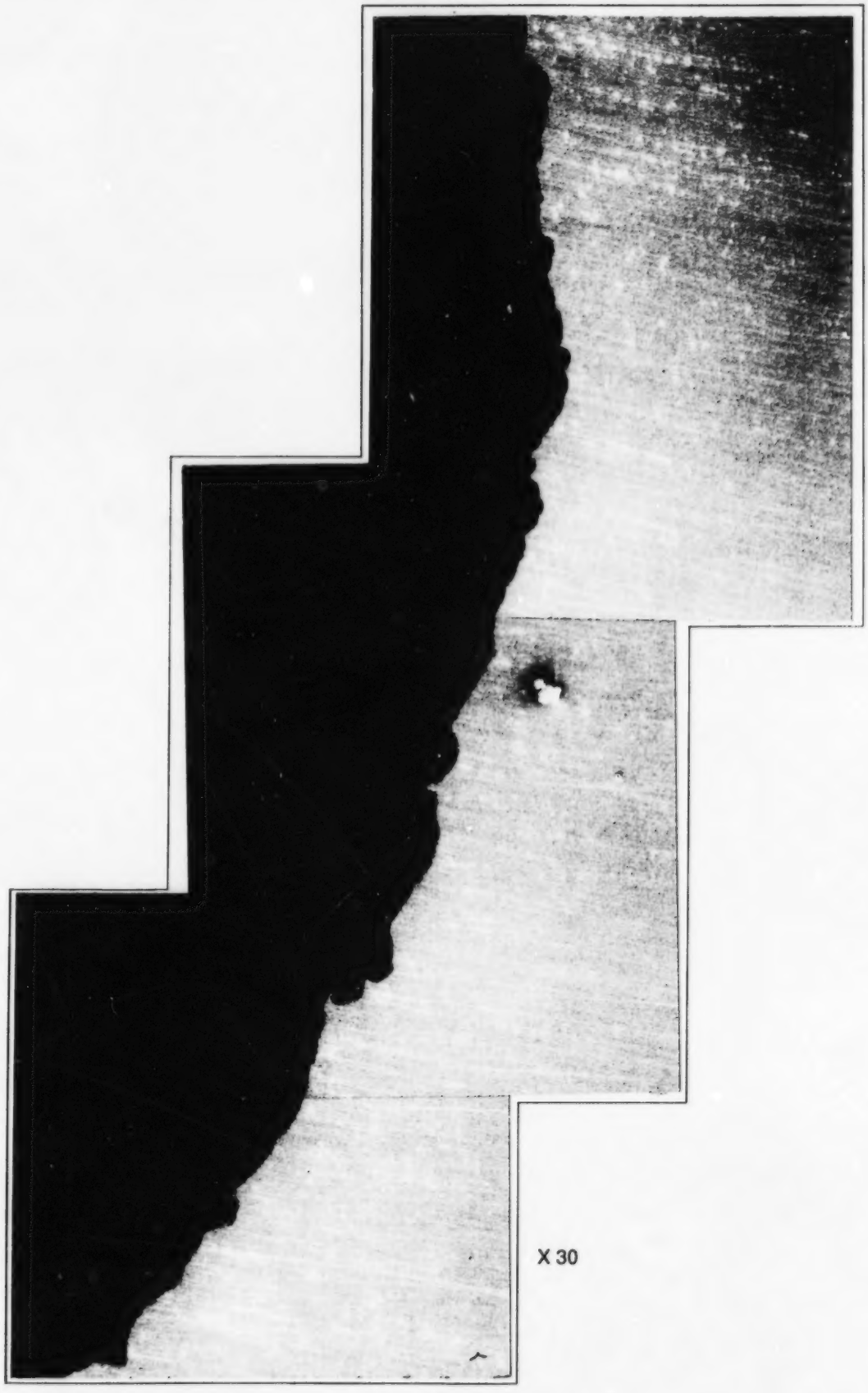
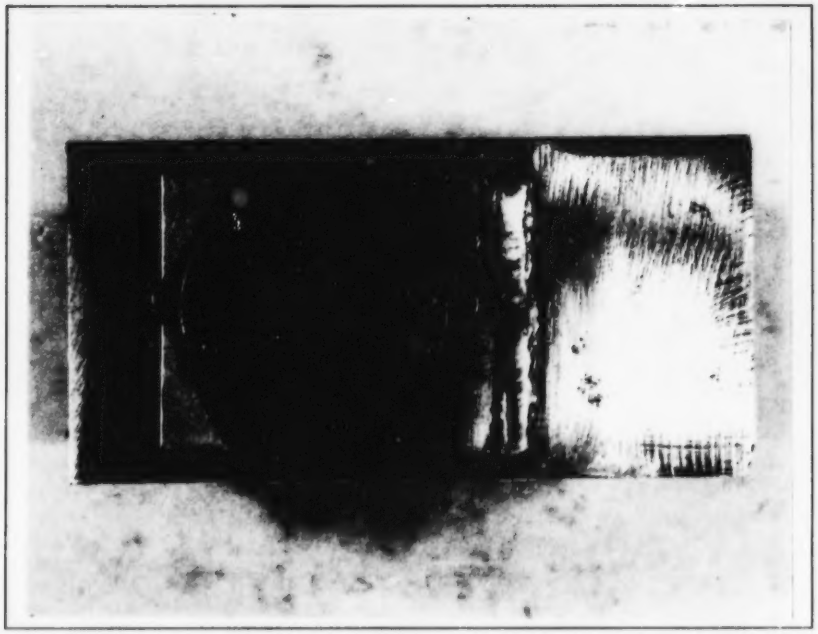


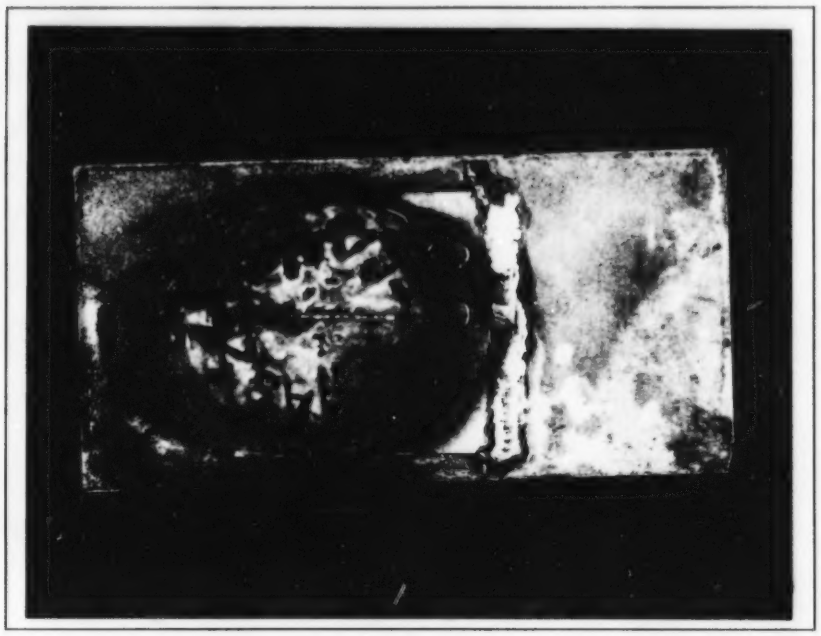

FIGURE 17

SHROUD FOOT WELD AFTER CHEMICAL CLEANING

91-4-K
184898-K14-RD



Before
Chemical
Cleaning

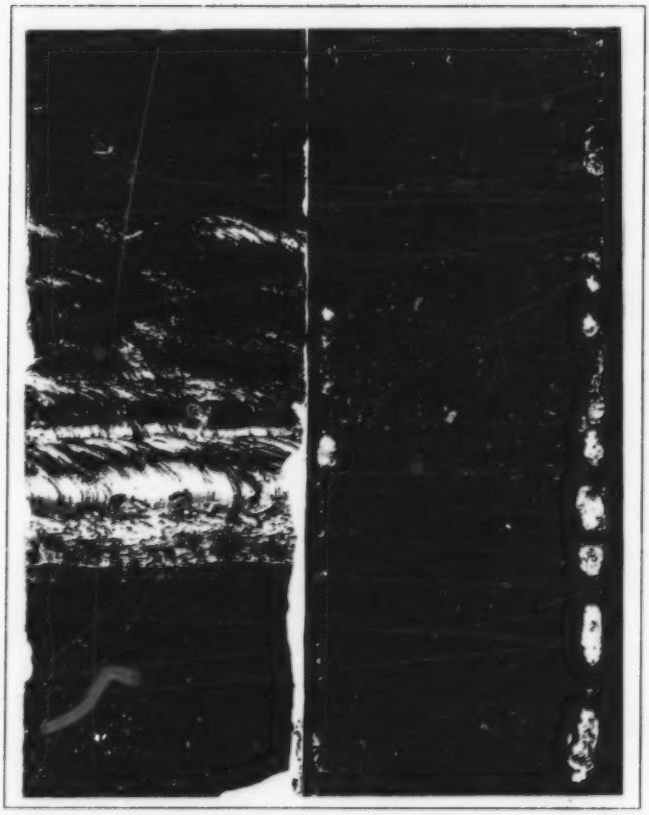


After
Chemical
Cleaning

**FIGURE 18**

**LOCKING TAB CORROSION TEST SPECIMEN**

91-4-K
184899-K14-RD

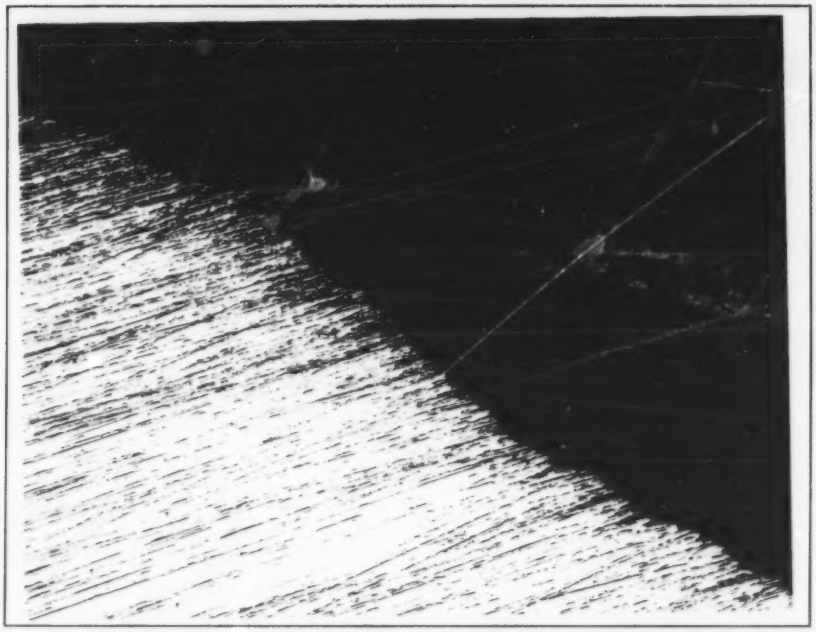


Before Chemical Cleaning

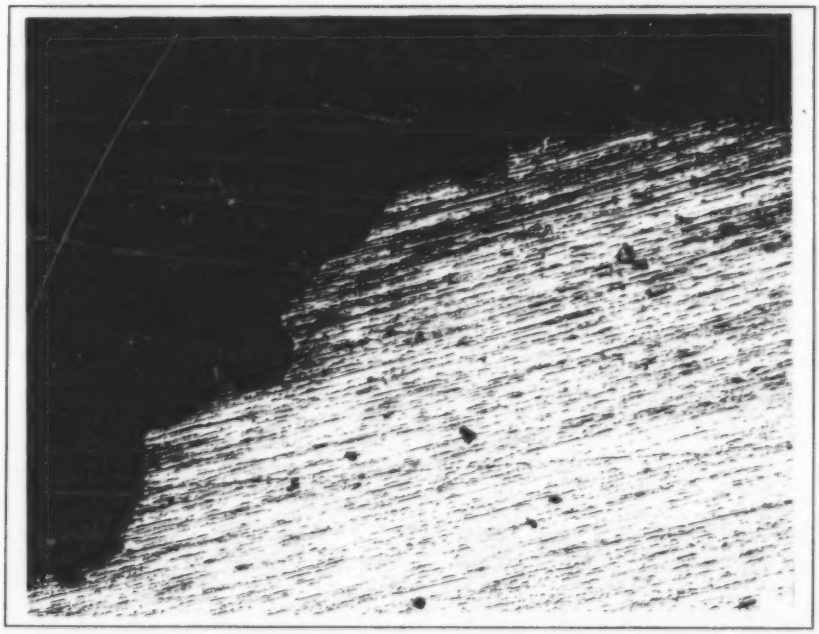
After Chemical Cleaning

**FIGURE 19**

**SHROUD SEAM CORROSION TEST SPECIMEN**



Before
Chemical
Cleaning
X 50

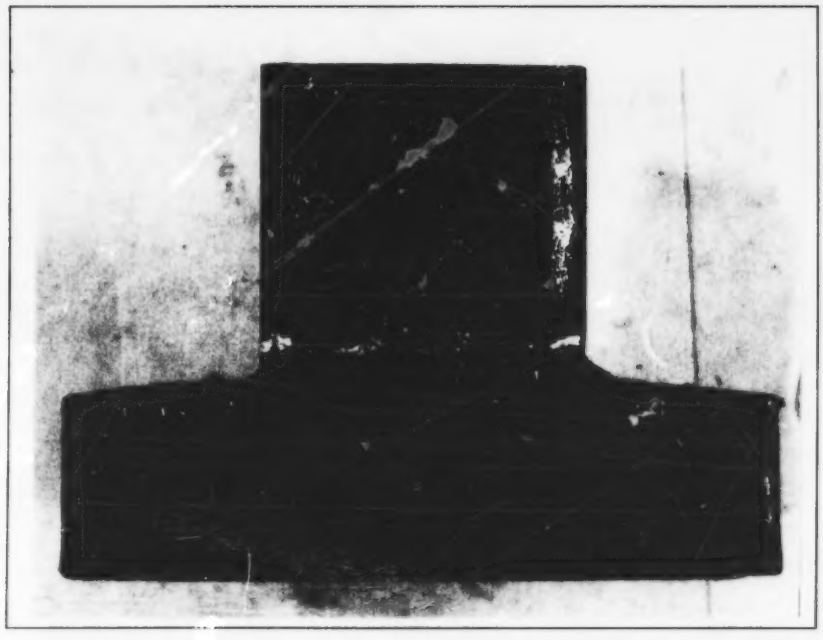


After
Chemical
Cleaning
X 50

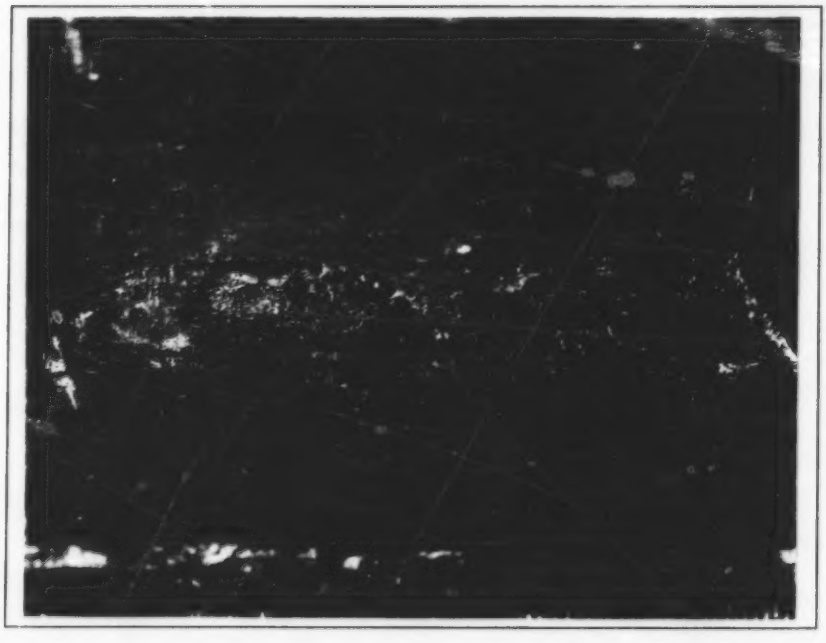
**FIGURE 20**

**SHROUD SEAM WELD**

91-4-K
184901-K14-RD



Before
Chemical
Cleaning

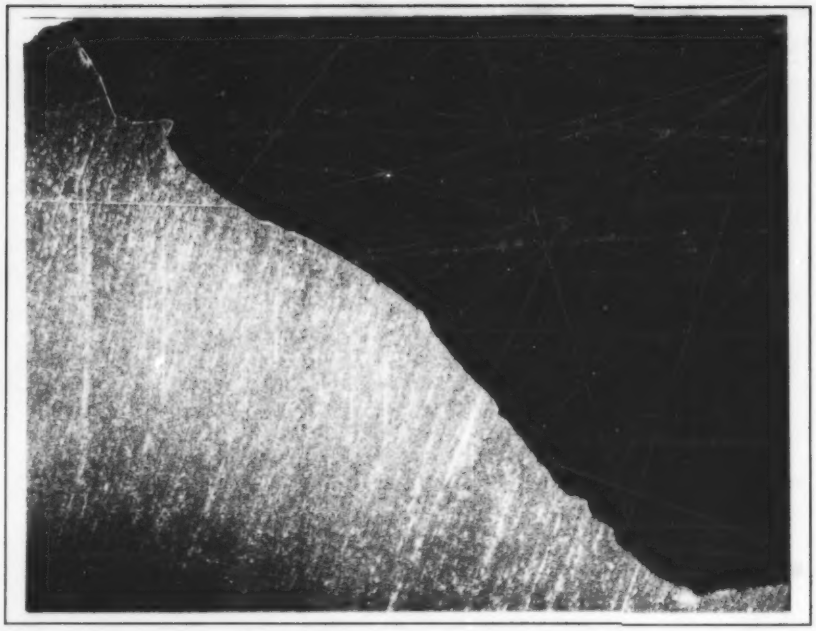


After
Chemical
Cleaning

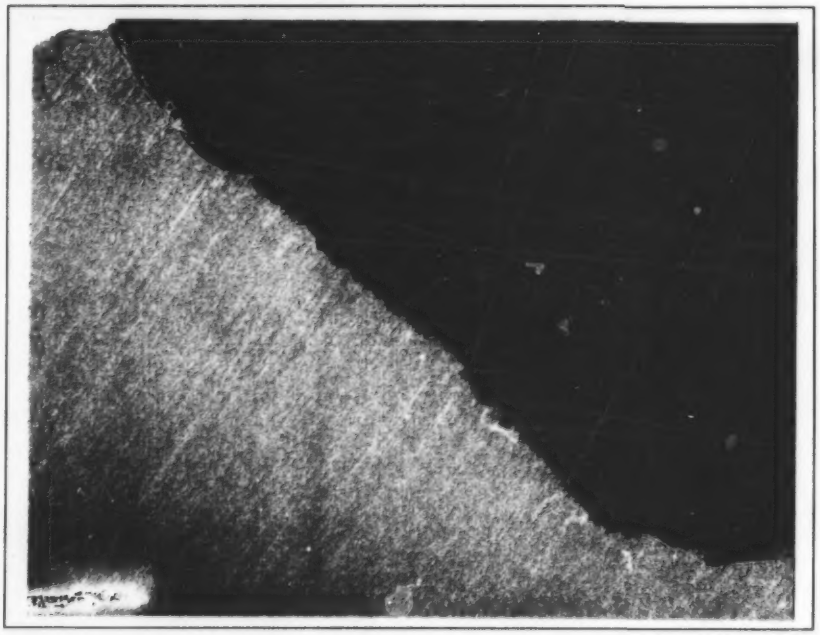
**FIGURE 21**

**BLOWDOWN HEADER TO SHROUD CORROSION TEST SPECIMEN**

91-4-K
184902-K14-RD



Before
Chemical
Cleaning
X 15

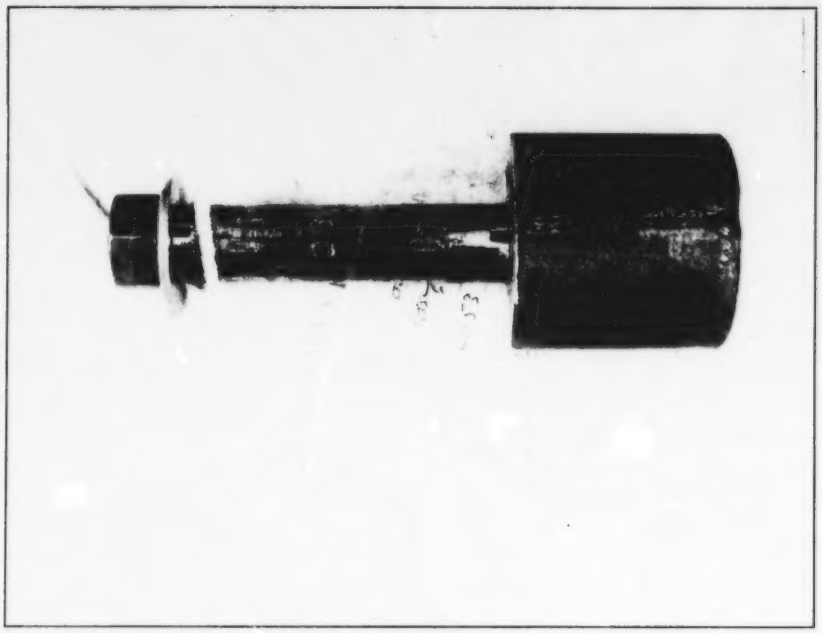


After
Chemical
Cleaning
X 15

**FIGURE 22**

**BLOWDOWN HEADER TO SHROUD WELD**

91-4-K
184903-K14-RD



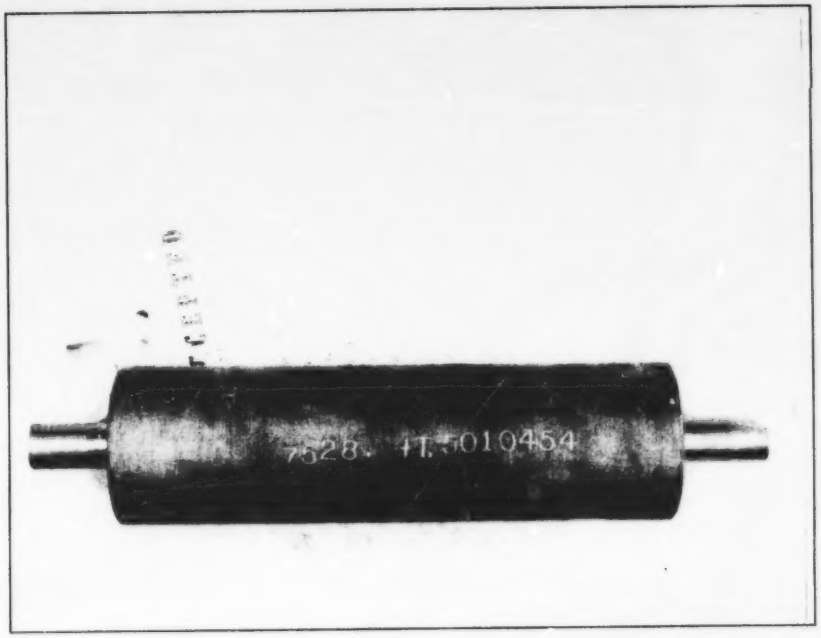
Before Chemical Cleaning

After Chemical Cleaning

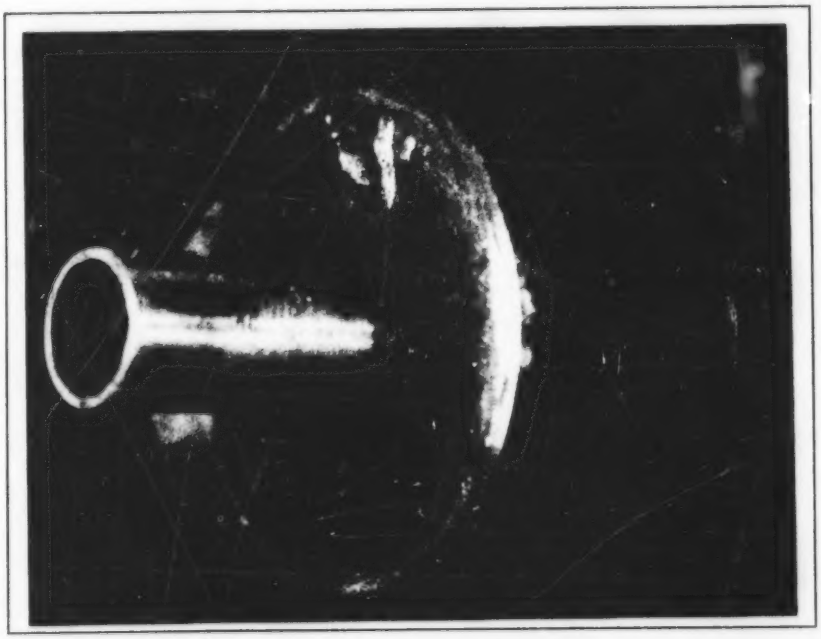
**FIGURE 23**

**TIE-ROD AND SLEEVE CORROSION TEST SPECIMEN**

91-4-K
184904-K14-RD



Before Chemical Cleaning



After Chemical Cleaning

**FIGURE 24**

**TUBE IN SLEEVE CORROSION TEST SPECIMEN**

91-4-K
184905-K14-RD